Final Publishable JRP Summary for ENG63 GridSens
Sensor network metrology for the determination of electrical grid characteristics

Overview

As electricity networks evolve to accept more distributed renewable energy generation, it is vital that sufficient information about current, voltage and frequency exists to manage and control them; enabling grid stability and reducing the possibility of blackouts. Observation and control of electrical grids relies on a network of sensors so that the status of the network is constantly monitored, known as 'state estimation'. The majority of research into controlling networks relies on knowledge about the structure of the network combined with modelling, or simulation, of the network. However, in practice the topology and impedances, or resistance to AC current, of distribution networks are often poorly documented due to inaccurate network circuit diagrams, uncertain connections or missing information. This project developed techniques to enhance the capabilities of sensor networks, to estimate missing information and to validate new algorithms for optimal sensor placement. The results were then demonstrated on real networks, and shown to improve the monitoring and knowledge of electrical distribution grids to improve security and reliability.

Need for the project

As electricity networks become more complex with distributed renewable generation and two way flows (i.e. consumers using electricity as well as putting it back into the grid), it is vital that sufficient information exists for their management and control. The precise structure and topology of distribution grids are often not known; however this information is required if retrofitted distributed renewable generation is to be installed and used reliably, whilst maintaining a stable and controllable network.

In order to promote a pan-European electricity network, the sensor network metrology must meet the requirements of the diverse range of distribution networks in place throughout Europe and support the design of new standard European smart grids, which can manage the two way flow of current, the billing requirements and network control.

Sensors installed in distribution grids can either be power meters (used for billing purposes) or more advanced and accurate power quality analysers, e.g. Phasor Measurement Units (PMUs) (for monitoring the network). As the measurement needs of distribution grids change due to increased renewable energy generation and changes in demand, it is essential that the best use is made of currently installed equipment and that the installation of new equipment is well informed. Advanced instrumentation such as PMUs is expensive but could add significant value to distribution grid measurement systems, enabling accurate grid monitoring and ultimately stability of a complex network. However, the costs and benefits of such technology can only be assessed through a greater understanding of how distributed measurement systems work and how to determine their optimum placement.

A smart grid is an electrical grid which includes a variety of operational and energy measures including smart meters, smart appliances, renewable energy resources and energy efficient resources. Ideally sensors would be placed at every node or branch to monitor the network. However this is currently impractical and uneconomical. Therefore, a compromise is needed between the cost of purchasing and placing a large number of sensors in a grid and the accuracy of the knowledge about the state of the grid. Sensor networks also need to be optimised to provide the necessary information to control the smart grid at the distribution level, whilst

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minimising the cost of the required sensors. Modelling or simulation of networks is an important part of understanding the network behaviour.

Algorithms specify how to solve problems or perform calculations, data processing and automated reasoning tasks. In the case of smart grids, algorithms are required to deduce the "state" (power flow and nodal voltages) and topology of the network and to optimise the placement of sensors (e.g. PMUs).

It is also essential that the data flow between all components of the sensor networks is secure and reliable. Electrical grids are at risk from cyber terrorism, which could result in damage to equipment and widespread long term blackouts. New standards are emerging to ensure security concerns are addressed as grids evolve. Smart grid measurement systems must fulfil the requirements of these standards and the implications of such security measures on the uncertainty of sensor networks and their dynamic behaviour need to be addressed.

Scientific and technical objectives

The project addressed the following scientific and technical objectives:

- To develop and test sensor network metrology algorithms for static and dynamic state estimation and optimal sensor placement.
- To investigate the use of PMUs for power flow calculation and state estimation in grids.
- To determine uncertain distribution network topologies and line impedances and verify existing grid models using a series of on-site measurements and state estimation techniques.
- To apply Smart Meter data to network state estimation.
- To implement and validate a secured standardised distributed measurement system in LV microgrids and to address the impact of security measures in the measurement system on the metrological requirements and uncertainties.

Results

To develop and test sensor network metrology algorithms for static and dynamic state estimation and optimal sensor placement

At present, distribution networks are made up of a large number of nodal points with limited monitoring. Knowledge of the "grid state", i.e. the nodal voltages and branch power flows, is essential for effective planning and operation. Estimation of these values can currently be done using state estimation algorithms, which use a number of real measurements combined with "pseudo measurements", usually derived from estimates of power demand obtained from past usage information. The accuracy, hence usefulness, of the information is dependent on the accuracy of the state estimation algorithms and the quality of the measurements. The project concentrated on two challenges:

1. Improving a Dynamic State Estimation algorithm, known as the Nodal Load Observer (NLO), which analyses trends in grid power flow data to estimate the state of the grid. The developments were demonstrated on real grid data and improved the performance of the algorithm, giving more accurate estimates of nodal voltages and power flows. Comparisons with real measurements showed that the NLO was able to provide accurate estimates when limited measurement data was available and pseudo-measurements were employed.
2. Developing optimal sensor placement algorithms that determine the best measurement strategies to recover an accurate picture of grid state for the lowest number of sensors. The project developed a new estimation method to enable more effective and efficient optimal placement algorithms to be developed and tested. In theoretical simulations the new estimation method was shown to work at least 10 times faster than previous techniques with up to a 5 fold improvement in accuracy.

Sensor placement algorithms incorporating the new state estimation technique, were developed and tested on real grid data from distribution grids. The measurement strategies found by the algorithms were compared with randomised measurement site locations, and gave lower errors in the majority of cases for the grids tested. The algorithms were enhanced to take into account budgetary considerations so that the cost of sensors (including installation and maintenance costs, which could vary considerably for different measurement locations) could be included.

In summary this objective was fully met and algorithms for state estimation and sensor placements have been developed and applied to simulated networks and several real grids.

To investigate the use of PMUs for power flow calculation and state estimation grids

For effective grid control the sensor network must be optimised to provide the necessary information to control the smart grid at the distribution level, while minimising the cost of the sensors. The project investigated the use of PMUs which although expensive could prove to be cost effective.

The NLO algorithm developed in objective 1 was applied to the ENDURIS grid in the Netherlands, which has a number of PMUs installed by VSL as well as standard monitors at the same locations as part of its SCADA (Supervisory Control and Data Acquisition) system. The performance of the state estimators was shown to improve as the number of PMUs measurement sites were increased.

Static state estimation algorithms were also run for the other real grids simulating PMU data by reducing the uncertainties of simulated voltage measurements. The simulations showed that the uncertainties in the state estimation are significantly reduced with a small number of PMUs, but with the addition of more PMUs a much smaller improvement is seen. The precise variation of uncertainty with the number of PMUs depends on the size and complexity of the network.

An enhanced sensor placement algorithm, which was able to consider a cost budget as well as accuracy, was used to perform a cost benefit analysis of PMUs for grid monitoring. Such analysis can now be applied to any distribution grid to allow network operators to make decisions on whether it is worthwhile to install PMUs on their grids.

In conclusion, the project has proved that the use of PMUs in state estimation can significantly reduce the uncertainties and be cost effective. It also demonstrated effective methods to determine where PMUs should be placed.

To determine uncertain distribution network topologies and line impedances and verify existing grid models using a series of on-site measurements and state estimation techniques

As distribution grids develop and evolve over many years, there is often a lack of up-to-date plans of their exact configuration. This may be because some of the original plans date back over several decades, hence there are often repairs and updates without documented details or changes in connections due to faults. Knowledge of the correct topology is essential for safely restoring grid operation after outages, failure identification and grid reconfiguration.

The project made adaptations to the Dynamic State Estimation Algorithm (NLO) and static state estimators, both developed in objective 1, in order to take into account uncertainties in line impedances and to determine unknown line impedances. Two algorithms were developed to recover unknown connections from uncertain distribution network topologies. Both algorithms were tested using simulated and real topology data. The real networks have known topologies so can be used to create missing nodes to be used as test data. Both algorithms were found to be effective at recovering missing connections.

In summary the project found that topology estimation is an extremely challenging problem and successful testing of such algorithms with real network data is important for demonstrating that the algorithms can be applied successfully.

To apply Smart Meter data to network state estimation

Smart meter data obtained from individual households has the potential to provide useful information at the distribution level particularly if the data can be aggregated to a single point e.g. at the distribution substation. This could minimise or avoid the necessity to install new measurement equipment at the distribution level.

An aggregation method was developed, implemented and tested using real and simulated distribution grids with anonymised customer data. The uncertainty for the aggregated data was typically found to be double that of the individual smart meters (around 1 %), this is better than the 10 % figure assumed in some existing literature and much better than the 30 – 50 % sometimes used.

In conclusion the use of aggregated smart meter data could be a cost effective way to improve the ability of a network operator to determine a complete picture of the power flows in their distribution grids, even if they only possess a small number of measurement points.

To implement and validate a secured standardised distributed measurement system

To provide the necessary information for smart grid observation and control, a sensor network requires a large amount of measurement and control data to be transmitted to a central location using different communication paths. To do this over an insecure network is a security risk and may leave the grid open to cyber-attack.

A review of the architecture of distributed measurement systems on smart grids was carried out and typical network and measurement system structures reproduced on a laboratory-scale LV microgrid at partner TUC. A Public Key Infrastructure (PKI) was retrofitted on a variety of instruments on this microgrid, including a common power meter. PKI was chosen as it is the most common way to communicate over an open network securely e.g. internet banking uses a PKI. The security recommendations and guidelines for secured communication that are provided by the Federal Office for Information Security Germany (BSI) and NIST (the National Institute of Standards and Technology in the US), were also fully implemented. This infrastructure was successfully demonstrated in real time by means of a communication link over the internet with PTB. The results showed that the prototype of the secured measurement system could satisfy most performance requirements of microgrid applications.

The project demonstrated a successful implementation of a secure communication system that can be used for protection of smart grids against cyber threats. The project also led to the creation of a European facility to test other implementations of possible security measures.

Actual and potential impact

Dissemination

A total of 14 peer reviewed papers have been published or approved for publication and 7 more have been submitted during this work. The consortium has presented its work 13 times and given a poster presentation at conferences including Conference on Precision Electromagnetic Measurements (CPEM), the international measurement confederation (IMEKO) and CIRED (the leading forum where the Electricity Distribution Community meets).

Two workshops were held by the consortium. A mid-project workshop was held at the University of Strathclyde, UK in associated with a Researcher Excellence Grant (REG(STRAT). The workshop was attended by 40 attendees from NMIs, industry and academia. This was also a joint workshop with ENG52 Smart Grid II.

The second workshop, at the end of the project, was held in Haarlem NL and was attended by more than 70 attendees from NMIs, industry and academia. This was a combined workshop of all the EURAMET projects on Electricity Grids finishing in 2017 (ENG61 FutureGrid & ENG52 Smart Grid II and ENG63 GridSens) and was attended by stakeholders.

The project was publicised in Smart Grid Today, www.smartgridtoday.com, an online trade journal dedicated to smart grid related topics. It was also publicised in the Elektor magazine, www.elektormagazine.com, which has an international audience of professionals and non-professionals interested in electronics.

Details about two new e-training packages and the relevant Good Practice Guide on how to employ them are available on the project website.

- A best-practice guide for quasi-dynamic state estimation with the NLO algorithm
- A guide on how to employ security algorhtms to create a PKI

Three training sessions took place with Distribution Network Operators that were involved with the project on the requirements of grid data for testing of state estimation algorithms. In addition a PMU manufacturer gave 1-2-1 training to the consortium on how to use its data analysis software.

Standards

Members of the consortium are active members of the relevant working groups of standards committees. The security systems developed in this project were used to inform them of how to achieve a homogenised approach in LV microgrids, which are small self-contained networks capable of operating independently of the wider grid and are becoming more important as local renewable generation increases. Information and results of the measurement security work has been regularly sent to the CEN/CENELEC/ETSI standardisation process under the EU mandate M/490. A report by the committee on the standards requirements for smart grids has been published along with a further document on cyber security:

ftp://ftp.cencenelec.eu/EN/EuropeanStandardization/Fields/EnergySustainability/SmartGrid/SmartGridSetOfStandards.pdf

ftp://ftp.cencenelec.eu/EN/EuropeanStandardization/Fields/EnergySustainability/SmartGrid/CyberSecurity-Privacy-Report.pdf

In addition, the consortium contributed to IEC SC77A WG1 on a draft standard governing the use of signalling on the mains electricity supply.

Actual impact

The project was predominantly focussed on the application of algorithms to real distribution grids, which required continued engagement with network operators throughout Europe, who are the most important end users of the project outputs. The consortium's findings are now available to them and, as a result of the close cooperation, can be easily used by them.

This project will enable network operators to improve their systems by:

- Providing a validated Dynamic State Estimation algorithm, the NLO that is able to provide an accurate picture of the grid state in real time.
- Providing robust validated sensor placement algorithms that not only take relevant uncertainties into account but also budgetary considerations.
- The demonstration that PMUs (an advanced and relatively expensive type of sensor) can successfully be used in a cost effective manner to significantly improve estimates of grid state and therefore the ability of network operators to control their distribution grids.
- Providing validated algorithms that allow network operators to recover missing grid topology (line impedance and connection) information.
- Demonstrating that aggregated smart meter data can be used to improve the ability of a network operator to determine the state of their distribution grids if they possess a small number of measurement points.
- Demonstrating that PKI secures sensor network systems used for grid monitoring from cyber-attack.
- Providing a European test facility suitable for characterising security measures on LV microgrids.

Potential impact

This project will enable network operators to plan their network to be robust and secure, as well as cost effective. By minimising the number of expensive PMUs and deducing the full network topology, future network operators will be able to use renewable sources without compromising network security or power quality.

List of publications

- On The Evaluation Of Uncertainties For State Estimation With The Kalman Filter S Eichstädt, N Makarava, C Elster *IOP Measurement Science and Technology* Vol. 26 (2016)
- Uncertainty Analysis of Aggregated Smart Meter Data for State Estimation F Ni, P H Nguyen, J F G Cobben, H E van den Brom, D Zhao, *2016 IEEE International Workshop on Applied Measurements for Power Systems (AMPS) Proceedings,* Aachen, Germany, pp. 13-18 (2016)
- Enhancing Prony's Method By Nuclear Norm Penalization And Extension To Missing Data S Chetien, *Signal, Image and Video Processing* Vol 11, Issue 6, pp 1089–1096 (2017)
- On The Pinning Controllability Of Complex Networks Using Perturbation Theory Of Extreme Singular Values - Application to Synchronisation In Power Grids S Chretien, S Darses, C Guyeux, P Clarkson, *Numerical Algebra, Control and Optimisation* (2017)
- Methodology For Testing Parameter-Free Fault Locator For Transmission Lines M Popov S Parmar, G Rietveld, G Preston, Z Radojevic, V Terzija *Electric Power Systems Research* (2016)
- Basis-Adaptive Sparse Polynomial Chaos Expansion For Probabilistic Power Flow F Ni, P H Nguyen, J F G. Cobben, *IEEE Transactions on Power* Systems, Vol 32, No. 1 (2017)
- Pmu-Based Power System Analysis of A MV Distribution Grid N Save, M Popov, A Jongepier, G Rietveld, *Proceedings of CIRED 2017* (2017)
- Application Of Non-Intrusive Polynomial Chaos Expansion In Probabilistic Power Flow With Truncated Random Variables F Ni, P H Nguyen, J F G Cobben, *Probabilistic Methods Applied to Power Systems (PMAPS)* (2016)
- Measurement Of The Harmonic Impedance Of The Aggregated Distribution Network V Cuk, F Ni, W Jin, A Jongepier, H E van den Broom, G Rietveld, M Acanski, J F G Cobben, *ICHQP 2016,* Belo Horizonte, Brazil, pp 739 – 744 (2016)

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